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Research report

Validation of a multidirectional locomotive dual-task paradigm to evaluate task-related differences in event-related electro-cortical activity

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ABSTRACT

A fundamental aspect of everyday function is the ability to simultaneously execute both cognitive and motor tasks. The ability to perform such tasks is commonly assessed using a dual-task paradigm that has the capacity to manipulate both cognitive and motor components of an action. Dual-task performance provides an opportunity to obtain an insight into how cognitive and motor function are affected during natural tasks (e.g., locomotion). The following study aimed to determine the effectiveness of using a goal-directed multidirectional locomotor task to measure differences in task-related (tasks of increasing difficulty) electro-cortical activity. In the single-task condition participants walked around a grid-based track, performing directional changes at each intersection in response to a sensory stimulus. In the dual-task condition participants performed the same primary task while performing a simultaneous memory recall task. Behavioural differences in trial completion time and electro-cortical activity were identified in relation to the posterior N2 and P3 component mean amplitudes. The results showed that, while performing a higher-level cognitive task during walking (dual-task), interference arises in a shared system that influences neural mechanisms involved in attention and selection for action, and later cognitive processes recruited in working memory and cognitive control. This study extends previous work and shows that performing a more complex cognitive task while walking, elicits interference effects sensitive to higher-level cognitive processes, and takes the next step towards measurement of electro-cortical activity within naturalistic environments.

1. Introduction

As we move through and navigate real-world environments we carry out a number of tasks simultaneously, for example, whilst walking in a shopping mall we can mentally rehearse and update a list of items we are looking to buy, or hold a conversation with a friend as we traverse a route. Pashler [1] has suggested that in real-world situations individuals often seem well able to perform two or more concurrent activities, especially when the tasks are compatible. However, the results of laboratory based experimentation suggest otherwise, with decrements in performance often accompanying processing on pairs of tasks [2,3]. Findings of dual-task research have identified alterations in spatiotemporal gait parameters that include reductions in velocity, changes in stride length and stride time variability [4,5]. This alteration during dual-task performance has been proposed to be associated with higher-level control of cognitive mechanisms involved in the control of gait speed [5]. Furthermore, evidence from neuroimaging studies have reported the involvement of prefrontal brain regions in the planning, preparation, execution and speed of gait [6], with these same regions also involved in higher-level cognitive processes, such as regulation of goal-directed behaviours [7]. A recent review reported the discrete and mutual cortical regions involved in gait execution and gait planning as so called 'direct' and 'indirect' locomotor pathways in the brain [8]. Functional brain regions involved in the planning of gait recruit the dorsolateral prefrontal cortex and the basal ganglia, whereas the execution of gait involves regions of the pre- and post-central gyri [8,9]. To evaluate the influence of dynamic tasks, such as walking, upon the time course of interference effects on neural activation, paradigms incorporating naturalistic whole body movement are required.

Currently, cognitive neuroscience strategies are employed to study electro-cortical signals sensitive to sensory and higher-level interference effects in a number of dual-task paradigms [1,10]. A dual-task methodology can address the question of whether discrete neural mechanisms are engaged when a secondary task is performed. For

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example, a decrement in walking performance when undertaking a concurrent cognitive task would be evidence for overlapping neural mechanisms and interference in a shared system [10].

Current research investigating the complex interplay between cognition and walking has failed to address two particular issues, the first of which is directly related to an unequivocal understanding of the functional attributes used to elicit dual-task interference effects and the resulting 'compatibility' effects that arise from task overlap under such conditions. Clarifying interference effects for shared resources between particular cognitive tasks and walking requires a precise index of the functional characteristics of stimulus and task related effects, thus providing an accurate means to assess the nature of task overlap leading to competition arising from engagement within a shared system. To date, contemporary research has failed to completely satisfy this criterion (See Al-Yahya et al., [5] for a discussion of this point). Non-adherence to such protocols in dual-task experimentation means that secondary (concurrent) tasks often engage non-specific cognitive tasks (e.g., taxing undefined higher-level cognitive and/or lower-level/perceptual processes) leading to ambiguity in the interpretation of results [5]. To determine the functional mechanisms that contribute to dual-task interference, the cognitive load manipulation used as a concurrent task with walking requires precise functional characterisation, in this way compatibility effects that arise from task overlap that tax higher-level cognitive mechanisms can be assessed. Walking is thought to engage cortical resources engaged in executive function tasks (e.g., prefrontal cortex and anterior cingulate cortex [11,12], in addition to low-level perceptual or motor response processes also engaged during walking [5,13,14]. As such, the functional characteristics engaged in a concurrent cognitive load task designed to elicit competition/interference effects in a walking paradigm require a well-designed and precise task protocol.

A second question that remains unanswered in studies investigating dual-task effects and walking is focused on the ecological validity of methodological approaches employed to evaluate interference effects. In the main, empirical studies using a dual-task methodology have been conducted in artificially controlled environments where individuals are required to maintain non-moving, often ridged, seated or laying postures. Until recently most research reports have made the assumption that the preparation of motor sequences and actions associated with real-world interactions are more or less automatic, and that perception and cognition can be studied as isolated neural events [15,16]. Recent advances in technology and signal processing techniques are leading to a paradigmatic shift focused on the study of mind in real-world situations [10,17,18]. This recognises the inter-dependent nature of sensory, motor and cognitive processing within dynamic environments [19,20], and provides an ecologically valid means to evaluate the adaptive and flexible [16] mechanisms that underlie many human activities involved in daily living, for example, walking and spatial navigation.

Within the dual-task literature, this paradigmatic shift is evident in the transition from the use of a seated paradigm [21], to the use of treadmills [17], and more recently with the development of mobile EEG systems, the evaluation of dual-task interference has been performed using a straight walking track [10] to investigate the relationship between cognition and walking. Evidence shows different patterns of electro-cortical activity associated with walking compared to stationary (seated or standing) conditions in the absence of any dual-task interference [17]. This includes an increase in activation within the anterior cingulate, posterior parietal, and sensorimotor cortex in the performance of steady-speed human locomotion on a treadmill [22]. Furthermore, a reduction in the mean amplitude of an N2 event-related potential (ERP) component thought to index the cognitive effort involved in the reception, integration, and processing of sensory stimuli has been reported as associated with dual-task processing [23,24], along with differences in the spatial-temporal distribution and amplitude of a later P3, an ERP component thought to index the allocation of attentional resources and working memory during dual-task performance [25–27]. In particular, a shift in topography of the P3 from a parietal to central maximal distribution (475–550 ms) between the single- and dual-task conditions and an earlier latency in the walking compared to seated condition has been reported [17]. Modulation in electro-cortical activity during the time window of the P3 are thought to reflect changes in neuro-cognitive processing under increased load within the walking compared to seated condition [17]. Put simply, differences in the P3 associated with additional load under dual-task conditions likely reflect the increased demand on attentional resources linked to the identification of stimulus processes involved in decision formation [28].

ERPs provide an index of the temporal sequence of neural activation involved in the mental representation of motor, perceptual and cognitive processes in the brain [29,30]. ERP components elicited around 200 ms after stimulus onset are thought to reflect the exogenous orientation of visuospatial attention which prioritises and enhances processing for goal relevant stimuli [30]. Research reports have shown that neural activation elicited in response to a visual stimulus and recorded at occipito-temporal electrode sites during the time interval between 200–350 m post stimulus onset as an N2 component provide an index of target detection [31] and cognitive control mechanisms in go/no-go tasks [17]. A recent dual-task study carried out using treadmill walking and seated conditions in a go/no-go paradigm reported a robust dual-task and walking (deliberately and briskly compared to sitting) effect as a reduction of the N2 component amplitude, which indicates susceptibility to increases in 'motor load' for the walking compared to sitting condition. This effect was thought to reflect automatic processing stages of inhibitory control on no-go trials [17].

Later ERPs following 300 ms after stimulus onset are thought to reflect the operation of higher level cognitive mechanisms in the brain, indexed by the P3 component and related to the allocation of attentional resources and working memory (WM) [25–27]. Results have shown that the P3 amplitude is reduced on dual-task conditions compared with single-tasks [32]. Moreover, according to 'resource models' such as the capacity-sharing model [1], when task demands interfere with the same cognitive resources there will be greater dual-task interference. The amplitude of the P3 is further reduced when the difficulty of a primary task is increased, in effect the perceptual-cognitive resources are thought to be depleted by the primary task [33,34]. To address the issue of determining the nature of the dual-task in order to clarify the distinct functional attributes associated with task-related effects, the current study aimed to employ two levels of interference during a walking task. The first engaged concurrent low-level sensory processing, and the second a higher level executive memory function task. In effect, this provided a means to contrast behaviour across three conditions of load, 1) free walking incorporating directional changes to the trajectory of movement (baseline-task (BT)), 2) walking and the orientation of attention to a concurrent low-level visuospatial cueing task (single-task (ST)), and 3) performance of the second task (walking and sensory) with the addition of a cognitively loaded task of rehearsing a shopping list in memory during trials (dual-task (DT)). To address the final point, the ecological validity of the methods employed to evaluate dual-task interference, the current study aimed to design a paradigm that would enable the use of electroencephalography (EEG) to evaluate electro-cortical activity involved in perception and cognition during naturalistic walking, that included the co-ordinated control of gait, maintenance of balance, and the negotiation of alterations to the trajectory of movement.

The main aim of this research was to develop and validate a multidirectional locomotive dual-task paradigm, by using fully mobile EEG. The goal being to assess both behavioural (task completion time) and electro-cortical activity (N2 and P3 ERP components) associated with performance on tasks that engage increasing sensory and cognitive demands and/or interference in an additive model as follows: Condition 1 (baseline-task BT) = route walking task. Condition 2 (single-task ST) = baseline walking task *plus* visuo-spatial directional task. Condition 3

(dual-task DT) = baseline walking task *plus* visuo-spatial directional task *plus* cognitive WM task. Based on previous research suggesting the involvement of the N2 and P3 ERP components in dual-task processing [17,32], it is predicted that the mean amplitude of the N2 ERP component would differ for both the ST and the DT compared to the BT, due to the capacity limited allocation of attentional resources engaged in early sensory and perceptual stimulus feature processing, In addition the mean amplitude of the P3 component would distinguish trials that engage greater cognitive load as in the DT condition as compared with the BT and the ST.

2. Materials and methods

2.1. Participants

Sixteen healthy males (n = 8) and females (n = 8) (*M* age = 27 ± 7 years; range 20–34 years) were recruited to participate in the study. Data from one male participant was discarded due to voluntary withdrawal. Thus, all analyses were conducted on the anonymised data from fifteen participants (7 males and 8 females). All participants provided informed consent and were healthy and reported being free of any neurological disorders and any medication that would influence central nervous system function. All procedures were conducted in accordance with the Declaration of Helsinki (http://www.wma.net) and were approved by the Human Research Ethics Committee, Victoria University, Melbourne, Australia.

2.2. Apparatus

A walking grid (21 m x 14 m) was created within a laboratory space by placing 48 mm wide tape on the ground. The grid was partitioned into 3.5 m x 3.5 m sections allowing the participant to perform a number of directional changes at each intersection (left, right, forward) (see Fig. 1). Marks were placed on the grid to provide a visual reference that signalled the start of a trial; these marks were placed at a point 1 m before each intersection. Reaching the marker initiated the wirelessly triggered onset of a visuospatial cuing stimulus (LED) that was used to indicate the direction of the turn at the subsequent intersection (left, right, and forward). The LED was attached, by way of an optic fibre cable, to a lightweight plastic glasses frame (see Fig. 2) and placed in a central position within participant's visual field and at a viewing distance of 11 cm from the nasion. The LED light (200 ms visual display time) was triggered via a wireless control with a temporal resolution in the order of < 1 ms when participants' reached the 1 m marker from the intersection. A receiver box, attached to the participant initiated the direction indictor LED light and sent a synchronous trigger/marker to the on-going EEG recording.

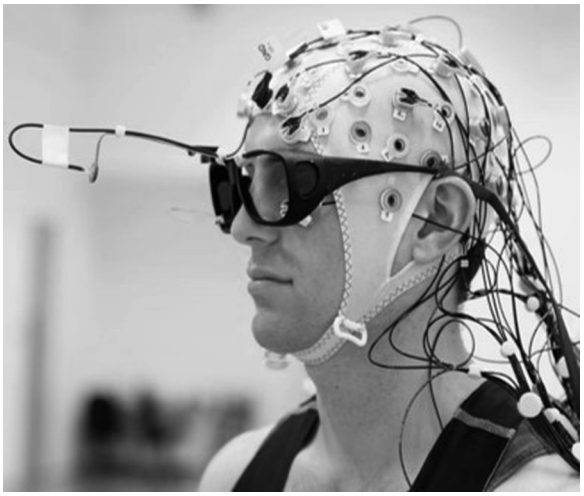

Fig. 2. Visuospatial cuing stimulus (LED light) attached via optic fibre cable.

2.3. Procedure

Screening measures and an initial health assessment were carried out to determine participants suitability to take part in the study, following this, EEG equipment was fitted and calibrated; participants then performed the locomotor task within the walking grid. Participants were instructed to fixate their gaze on the walking track and not on the LED light. The LED stimulus was visible within the participant's peripheral visual field. Experimental blocks consisted of a baseline (BT), single (ST) and dual (DT) condition. In the BT block participants walked around the track performing left and right hand turns or walking straight ahead at each of the intersections for 150 turns. The direction of turn was the participant's free choice, the LED light, had not been associated with directions at this point in the experiment. On completion of the baseline blocks participants undertook the ST and DT conditions, 150 trials in each. Before commencement of the ST and DT trial blocks, participants were given the assignment of LED light colour and the turn direction (left 90° turn = green; right 90° turn = red, forward = no light) to be performed at each intersection. Upon the participants foot transition over the 1 m mark from the intersection, the

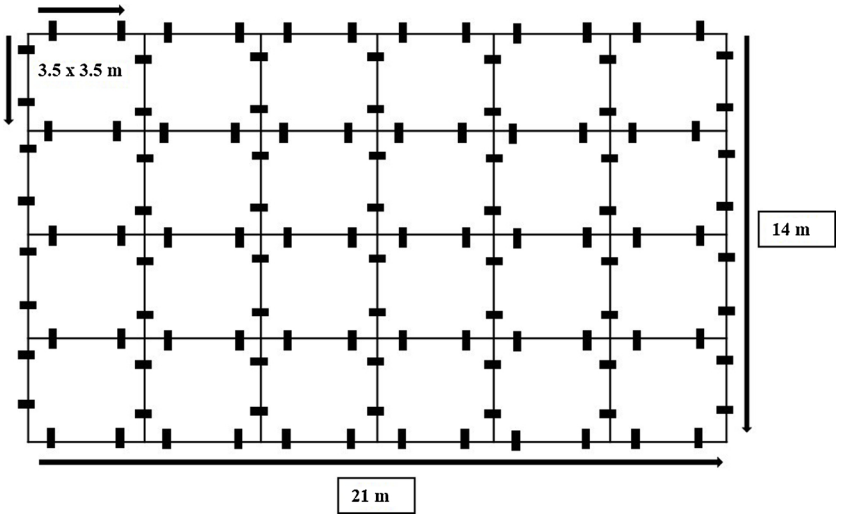

Fig. 1. Walking grid showing the 1 m marker () before each of the intersections.

LED light and EEG time stamp were wirelessly triggered, signalling the beginning of the experimental trial (150 trials per condition).

All participants performed all of the experimental conditions (BT, ST and DT). The presentation order of the ST and DT conditions were counterbalanced across participants, and each condition comprised three blocks of 50 random direction trials (150 in total). In the ST condition participants traversed the grid making directional changes, as indicated by the LED, at each intersection (see Fig. 1). EEG event markers synchronised (< 1 ms) to the onset of the LED and foot fall on the 1 m marker from the intersection were triggered wirelessly to the on-going EEG recording. EEG event markers synchronised to the onset of the LED were triggered wirelessly to the on-going EEG recording. Experimental procedures in the dual-task were the same as in the ST condition with the inclusion of a working memory (WM) task. The WM task involved participants being shown a list of 15 concrete nouns (for example, almonds, pizza, wine) at the beginning of each of the three blocks. Words were presented on an A4 sheet of paper (one word per sheet) at a rate of one word per two seconds. Prior to presentation of the 15 word list, participants were instructed to memorise three specific words (e.g., the 1st, 5th and 14th word). The words to be memorised were randomly selected across blocks. At the end of each block participants were then asked to recall each of the words, prior to being presented with the word list again (summation of a 1 min interval between each block).

2.4. Behavioural data analysis

Trial completion time was evaluated using the time it took a participant to walk through a 3.5 m section of track ending at each intersection. The average time to complete each trial was computed using the total time to complete each condition (not including inter-block periods) divided by the total number of trials (150). In order to determine the difference in the average time taken to perform each of the conditions (BT, ST and DT conditions), a fully within participant one way ANOVA was conducted using a 3 Condition (BT vs. ST vs. DT) on the dependant variable of trial completion time. Pairwise post-hoc contrasts determined significance of effects using the Bonferroni adjustment applied to alpha. Effect sizes for the pairwise comparisons were computed using Cohen's d, and standard error of the mean.

2.5. Electroencephalography (EEG) recording and data analyses

EEG was recorded using an actiCHamp amplifier (Brain Products, GmbH). The interface between electrodes on the scalp and the amplifier was provided by a Brain Products (GmbH) wireless MOVE System. A global positioning system harness was used to secure the wireless transmitter to reduce the risk of movement of both leads and transmitter components, in addition to lowering the risk of excessive tension on the electrode leads. Continuous EEG data was recorded using 24 channel Ag-AgCl active electrodes (Fp1/Fp2, F3/F4, FC1/FC2, FC5/FC6, Fz, C3/C4, TP9/TP10, CP1/CP2, CP5/CP6, Pz, P3/P4, P7/P8, O1/O2) placed in an elastic cap. ActiCap and PyCorder 1.0.7 software (Brain Products, GmbH) controlled the acquisition of EEG. Electrodes were placed in accordance with the international 10/20 system [35,36]. A ground electrode was positioned above the forehead (at Fpz), and all electrodes were referenced during recording to Cz. Additional electrodes were placed above and below the left orbit and the outer canthus of each eye to monitor bipolar electroocoulogram (EOG) activity. Electrocardiogram (ECG) electrodes were also placed below the collar bone on the mid and lateral aspect of the left side of the body on a 45° angle to monitor the ongoing EEG recording for heart rate artefact. A signal recording bandwidth of DC – 20 kHz was applied and a sampling rate of 1000 Hz and impedances were checked before and after each condition of testing and remained < 3 kΩ.. Due to issues of signal loss (wireless connection) during data collection, and removal of four dual-task trials due to the wrong direction being performed by the participant, on average 3% (SD 1%) of trials across all conditions were removed, leaving 99% for BT & ST (n = 2227 each condition) and 98% DT (n = 2205) trials being used for the subsequent ERP analyses.

Data were analysed off-line with the freely available MATLAB-toolbox EEGLAB [37] and digitally filtered off-line with a high (0.1 Hz) and low pass (40 Hz). Each participants' EEG was segmented into epochs time-locked to the onset of the stimulus triggers. Epoch lengths were 800 ms following and 200 ms prior to the onset of directional display. Baseline correction was carried out by removing the mean of the 200 ms baseline from the epochs. Physical online reference Cz (vertex) was retained for analyses of event-related potentials. For each participant Infomax independent components analyses (ICA) using runica algorithm returned 24 maximally independent components [38]. Following this DIPFIT2 routines EEGLAB [37] were applied to fit equivalent dipole models to the scalp topographies of the independent component scalp maps using a spherical (four-shell) head model [39]. Components with bilaterally distributed scalp maps were fit with a dual dipole model using a symmetrical constraint. Components that reflected muscle activity, electrocardiogram, eye movements and high frequency line noise were excluded from further analysis as were independent components whose equivalent dipole was identified as located outside of brain volume (neck and muscle activations).

EEG waveforms were identified using a collapsed localizer average for BT, ST and DT conditions [40] relative to a 200 ms baseline, triggered to the beginning of a trial. Electrode sites at bilateral parietal and occipital locations (P3/P4/P7/P8/Pz/O1/O2) were chosen based on the most pronounced voltage deflections identified in the grand collapsed averaged data and topographical maps and based on scalp sites previously reported in the literature [36,41]. The N2 and P3 components were defined as the largest going (negative and positive respectively) peaks occurring within a 50 ms time window for the N2 (200–250 ms) and a 100 ms time window for the P3 (400–500 ms). Mean amplitudes were computed for each condition across the respective time windows. Differences in electro-cortical activity from posterior parietal and occipital electrode sites were measured using within subject repeated measures ANOVA with 3 Condition (BT vs ST vs DT) by 7 Electrode sites (P3/P4/P7/P8/Pz/O1/O2). Pairwise post-hoc contrasts determined significance of condition effects using the Bonferroni adjustment applied to alpha. Violations of spherecity were adjusted with the Greenhouse Geisser Epsilon correction. Effect sizes were computed using the partial eta squared (η_p^2) for the within-subjects repeated measures ANOVA and Cohen's d for the pairwise comparisons, and standard error of the mean.

3. Results

3.1. Trial completion time

ANOVA for the trial completion time revealed a significant effect of condition ($F(2,42) = 10.01$; $p < .001$). Pairwise comparisons for the condition main effect revealed a significant difference in time between BT vs. ST (t (14) = -10.85, $p < .001$, $d = 0.95$), BT vs. DT (t (14) = -11.31, $p < .001$, $d = 0.95$), and ST vs. DT (t (14) = -3.23, $p = .01$, $d = 0.65$). This showed a relationship between increases in task complexity and slowing of trial completion time (see Fig. 3). On average participants recalled 2.6 words correctly in each block of the dual-task.

3.2. ERP results

Fig. 4 shows the grand averaged event-related potentials computed for the three conditions in the walking grid triggered on baseline-, single- and dual-task trials.

3.3. N2 ERP component

ANOVA for the posterior N2 (200–250 ms) component revealed a

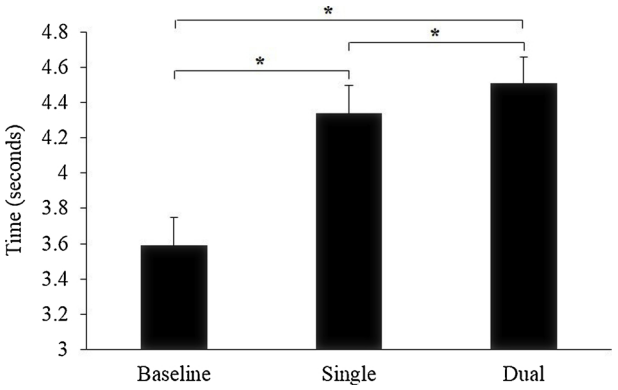

Fig. 3. Average condition trial completion time (baseline-, single- and dual-task). Data is presented as mean ± SE.

significant effect of condition ($F(2,28) = 12.52$; $p < .01$, $\eta_p^2 = .47$) but no interaction between condition and electrode site ($F(12,168) = 0.47$; $p = .75$, $\eta_p^2 = .03$). Pairwise comparisons for the condition main effect revealed a significant enhancement of the N2 component mean amplitude in the DT (M = -2.075 μV, SE = .24) vs. both BT and ST (M = -.763 μV, SE = .18 and M = -1.091 μV, SE = .20 respectively) conditions (t (14) = 4.97, $p < .01$, $d = 0.80$ and t (14) = 3.73, $p < .01$, $d = 0.71$ respectively) (see Fig. 4 for ERPs and Fig. 5 for topographic difference maps), but ST vs. BT did not differ (t (14) = 1.13, $p = .28$, $d = 0.29$).

3.4. P3 ERP component

ANOVA conducted for the ERP mean amplitudes of the posterior P3 (400–500 ms) revealed a significant effect of condition ($F(2,28) = 5.64$; $p = .01$, $\eta_p2 = .29$) but no interaction between condition and electrode site ($F(12,168) = 2.10$; $p = .10$, $\eta_p2 = .13$). Follow-up contrasts for the condition main effect revealed significantly enhanced P3 component mean amplitude in the DT (M = .924 μV, SE = .24) vs. both BT and ST (M = .338 μV, SE = .13 and M = .284 μV, SE = .21 respectively) conditions (t (14) = -2.33 $p = .04$, $d = 0.53$ and t (14) = -3.99 $p < .01$, $d = 0.73$ respectively) but not ST vs. BT (t (14) = 0.26 $p = .80$, $d = 0.07$) (see Fig. 4 for ERPs and Fig. 6 for topographic difference maps).

4. Discussion

A multidirectional locomotive dual-task paradigm was used to evaluate the effects of walking on perception and cognition within this study. Results revealed dual-task interference effects in both behavioural and electro-cortical measures that partially supported the experimental hypotheses. There was an increase in trial completion time across the different complexities of condition, with baseline (BT) walking producing the shortest overall latency, single (ST) being intermediate and dual (DT) taking the longest. Overall the pattern of ERPs were consistent with behaviour and go some way to support experimental predictions. Further, this study provides novel evidence of the effects of walking on the capacity to perform dual-tasks in a multidirectional locomotive task. Results revealed significantly enhanced N2 mean amplitude (200–250 ms) at posterior occipito-temporal electrodes, during the DT condition as compared with ST and BT. Importantly, no significant difference in ERPs during the time interval of the N2 time interval were found for ST compared with BT. A complex pattern of task effects was revealed during the time window of the P3 (400–500 ms), that likely reflect the unique contributions involved dual-task interference.

Results showed that during the early time interval (200–250 ms) over posterior electrodes the mean amplitude of the N2 component was enhanced for the DT condition as compared with both ST and BT. The finding of no significant difference in the mean amplitude of the N2 triggered on the walking trials (BT) involving free choice of direction as compared with trials including engagement with a visuospatial cueing task (ST) suggests that the neural mechanisms involved in these two conditions can operate in parallel without significant perceptual load or interference at the neural level. These tasks can be considered to be compatible, with no evidence for competition in neural cortices [10]. The finding of enhanced N2 amplitudes on trials involving engagement in a flexible WM shopping list task (DT) compared with both ST and BT is evidence of dual-task interference in neural processing. The perceptual and cognitive resources that are engaged in the DT condition produced competition for a limited set of attentional resources [42]. Posterior N2 negative going amplitudes are associated with selection negativity [43] involved in the orientation and allocation of attentional resources engaged in top-down control networks. Concurrent tasks that engage sensorimotor processing that involve the planning and execution of walking [10], as in the current DT condition, result in

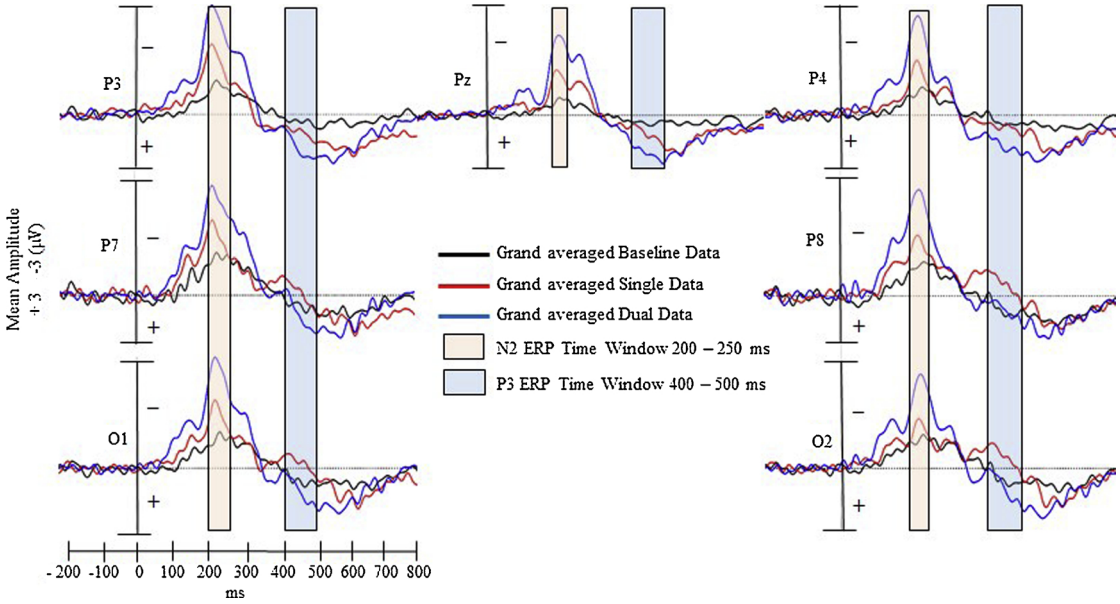

Fig. 4. Shows event-related potentials triggered on trial blocks in the baseline-, single- and dual-task conditions at posterior electrode sites.

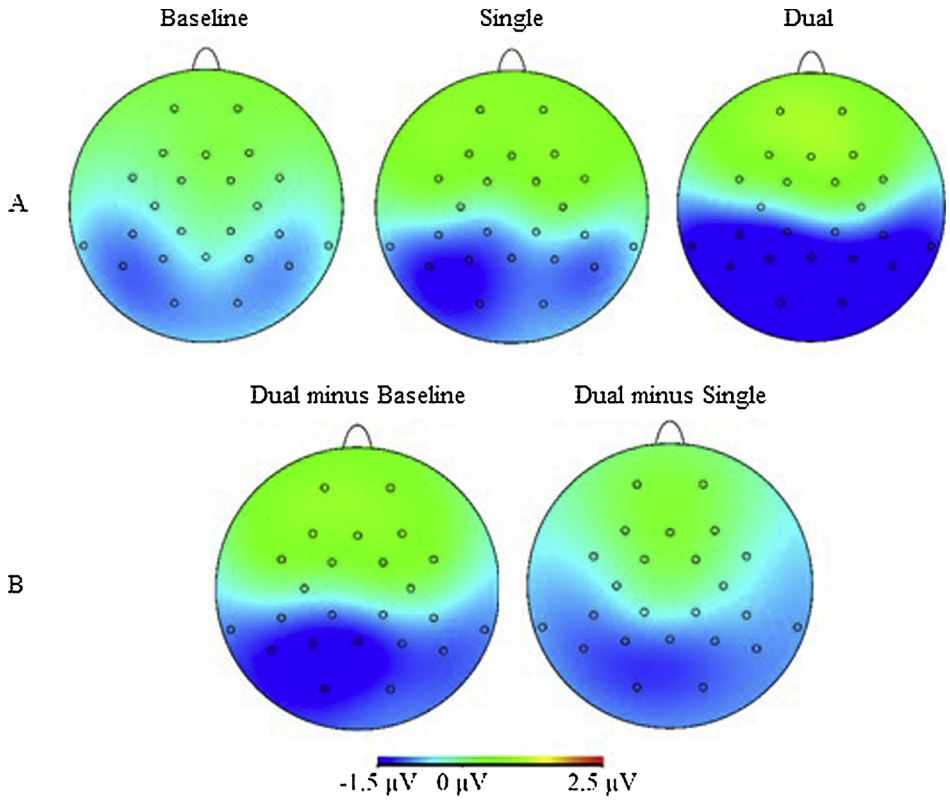

Fig. 5. Topographic scalp maps of the N2 electro-cortical mean activity across all conditions (Row A) and difference topographic maps plotted for contrasts that showed a significant difference in ERP mean activity (Row B) (200–250 ms).

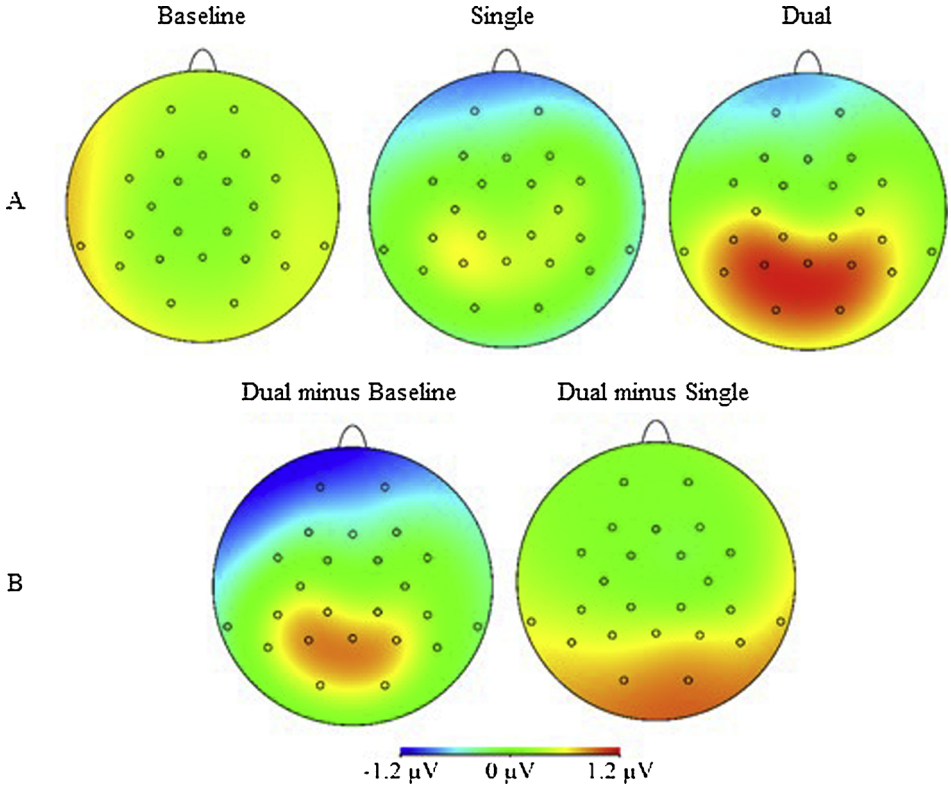

Fig. 6. Topographic scalp maps of the P3 electro-cortical mean activity across all conditions (Row A) and difference topographic maps plotted for contrasts that showed a significant difference in ERP mean activity (Row B) (400–500 ms).

competition for a limited attentional capacity [42]. The results of the current study suggest that DT trials engage neural systems whereby incompatible concurrent tasks compete for neural mechanisms involved in the deploying and orientation of attentional resources engaged in top-down attentional control networks and the sensorimotor processing involved in the planning and execution of walking [10]. The absence of a difference for N2 during ST and BT suggests that the low-level sensory processing engaged in the visuospatial task on the ST trials did not interfere with the motor control processes engaged on the walking task. Furthermore, this pattern of activity, likely reflect a modulatory effect that is not simply related to different motor demands (in the preparation for walking), but to differences in the cognitive requirements and working memory load (cognitive interference) between both BT and ST compared to DT conditions. Therefore, in the more complex (DT) condition, the N2 results indicate a similar pattern to those reported in the previous literature, that indicate an effect of cognitive interference in the form of attentional enhancement during stimulus evaluation [31] and degree of attention required for processing stimuli in the visual cortex [44], such as that associated with monitoring for the colour of the presented light stimulus and translation of this sensory information into goals and actions [45,46].

Posterior ERP selection negativity reported as an N2 component is considered to reflect the output of a number of sub-components [31] and is usually maximal at occipito-temporal electrode sites. The spatial distribution of N2 selective attention effects in the current dataset were prominent at inferior parietal sites suggesting contributions from an N2b component reported as engaged on tasks that require 'selection for action' [47] and thought to arise from neurons located in the anterior cingulated cortex [47,48]. The finding of dual-task effects with an N2b spatial and temporal distribution suggests interference effects that arise from a shared system between the higher level concurrent (cognitive memory) task and participant's engagement with the directional cue display. An additional feature of the current study was the use of Cz (vertex) as reference, a processing strategy used to minimize muscle/movement artefact in the data. However, the vertex reference was likely reflected in the spatial distribution of ERPs in the current data set (see Dien, [49], for a discussion on this point).

Supporting the proposal of cognitive interference effects in response to dual-task processing during the N2 are results of the current study which show modulations of the P3 (400–500 ms). Results revealed subtle differences reflecting task differences across the scalp as enhanced positivity at posterior electrodes sites. Posterior positivity during the P3 was enhanced for DT compared to both ST and BT at inferior bilateral parietal and occipital electrodes. The effects of the P3 have been reported as maximal over lateralised inferior-parietal regions (P3 and P4) [50], and is evident in the current data as an enhancement of the P3 in DT compared to ST and BT posteriorly. The enhanced posterior P3 triggered on DT trials is representative of increased activation within the focus of attention, namely greater WM, specifically through the encoding and retrieval phases of information processing [51–54]. However, the P3 has been found to reflect the strength of memory in serial encoding and storage tasks, with larger components reflecting recognition memory for particular serial list items [55]. This serial mechanism, is suggested to be closely linked to the bottleneck theory of dual-task interference, where due to a shared mechanism of processing task requirements, dual-task interference arises in the form of a delay or impairment in one or both tasks, further that task demands are processed in a sequential manner to overcome the bottleneck [1]. Moreover, that this inhibition of one task to process the requirements of the secondary task (e.g. the behavioural inhibition system) [56], is in line with previous research using such paradigms to induce an inhibitory-related enhancement in the P3 amplitude, as observed in this study. The results observed within this study are consistent with previous research that report an increase in P3 amplitude during complex tasks involving both phonological and visuospatial load, with phonological load promoting an enhanced P3 amplitude but not visuospatial load [57]. Furthermore, the P3 time window in the current study likely reflects the outcome of the recruitment of different neural generators involved in the spatial and verbal memory tasks [58]. This pattern of activation highlights the importance of clarifying the functional properties of task employed to elicit enhanced task difficulty (e.g., the difference between spatial and verbal memory tasks). In other words, verbal information (shopping list items) are processed intermittently in an updating manner, as opposed to being continually rehearsed and held in short term memory, leaving sufficient attentional focus and resources to manage the spatial navigation aspect of the task, reducing the level of conflict required to perform the task successfully [59].

The main purpose of this study was also to evaluate the relationship between behavioural measures of task-complexity in the form of dual-task performance and electro-cortical patterns of activation. Whereas, Beurskens et al. [10] found a significant effect of motor interference, and no effect of cognitive interference in the electro-cortical activity, in the present study, we observed the opposite. Decrements in performance were associated with electro-cortical activity associated with cognitive load manipulation. A key point of difference between Beurskens et al. and the current study, however, relates to the composition of the motor task. Beurskens and colleagues employed a 10 m straight walking track, enabling the participant to walk back and forth along the track. We employed a track configuration that required multiple changes in direction and more dynamic aspects of spatial navigation. This manipulation resulted in an increased demand and cognitive load as a consequence of participants holding in WM both information relating to directional commands and in the dual condition key words from a shopping list.

An increase in trial completion time is suggested to be associated with the additional processing incorporated within the dual-task load, such as alterations in gait parameters (e.g., decrease in stride velocity and increases in stride time variability) [10,60,61]. Of note, despite there being a difference in trial completion time in the ST compared to BT and DT conditions, aside for electro-cortical activity within the posterior region, no difference was observed between the BT and ST. Simply put, in the conditions requiring motor preparation (walking task) and responding to visuospatial cues (ST), no additional attentional cognitive resources are required to process these two components simultaneously. However, with the addition of the memory task within the DT, the active engagement in shopping list rehearsal consolidation was the catalyst for changes in electro-cortical patterns of activity.

The multidirectional locomotive dual-task paradigm employed in the current study acknowledges the interaction between the walking context and perceptual and cognitive functions that operate within everyday function. The continuous updating and adaption that occurs as individuals move within the real-world is included in the paradigm reported here. The novel, multidirectional locomotive, dual-task paradigm outlined in this study was designed to specifically examine task-related differences in electro-cortical activity during naturalistic walking and cognition. The method developed in this study provides an important advancement over existing dual-task paradigms. The primary advancements in the dual-task paradigm presented in this research are that it successfully manipulates both higher-level cognitive functions in the context of walking [11,12], and lower-level visuospatial and motor preparation processes during walking [5,13,14], and functionality that requires whole body movement and spatial navigation, therefore providing a platform that has greater applicability to how we interact and function in everyday activities. The methodological approach presented is a step towards evaluating cognition in more real-world contexts by employing directional trajectory changes along the path of travel moving from a treadmill and single direction track to measure ERP's in a more naturalistic multidirectional setting. The paradigm used within this study, however, is not without limitations, specifically in relation to more informative evaluation of gait. For example, in future research, accelerometers and gait analysis could be performed to evaluate the correlation between elector-cortical patterns of activity and changes in gait parameters under increasing cognitive loads.

5. Conclusion

The current study investigated the effects of gait execution/walking on the behavioural and ERP effects of perception and cognition under conditions of single- (visuospatial cue processing) and dual-task (the encoding, rehearsal and updating in memory of a complex shopping list). The results found early differences in the ERPs at posterior electrodes during the N2 component that distinguished the DT conditions with ST and BT during a time window associated with dual-task interference and an increase in attentional requirements related to selection for action, cognitive effort and perceptual load associated with the DT as compared with ST and BT. The pattern of results during the P3 suggests differences between the DT and both ST and BT conditions, with effects showing task incompatibility related to dual-task effects reflecting cognitive control and memory encoding and storage. The current study provides validation for the use of a novel multidirectional locomotive dual-task paradigm to evaluate cognitive and motor processing and interference using a more complex walking task than previously reported.

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Declaration of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.bbr.2018.12.039.

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